First Results of the Galileo Photopolarimeter/Radiometer on Jupiter and the Galilean Satellites

G. s. 01”1011,” J.R.Spencer, 1,. D. Travis, T.Z.Martin, L. K. Tamppari

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T. Z. Martin and G. S. Orton are at M.S. 169-237, and L. K. Tamppari is at M. S. 264-723, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; J. R. Spencer is at Lowell Observatory, 1400 Mars Hill Rd., Flagstaff, AZ 86001; and L. D. Travis is at the Institute for Space Studies, NASA / Goddard Space Flight Center, 2880 Broadway, New York, NY 10025.

Photopolarimeter-Radiometer (PPR) 200-km resolution maps of daytime temperatures on Ganymede show the expected anticorrelation with albedo, but morning temperatures are about 10 K warmer than expected. Europa has a subsolar temperature of 128 K, and a lower effective thermal inertia than Ganymede or Callisto, and Io's night side is cooler than predicted by recent models, perhaps requiring revision of heat flow estimates. Temperature maps show that the lowest 250-mbar temperatures in the Great Red Spot generally correspond to the visually darkest regions. Temperatures remain cold north of the GRS, but they rise by as much as $\sim$6 K to the south over the 2800-km PPR resolution. A visually bright region northwest of the GRS was also relatively cold. We suspect the influence of NH_3 cloud opacities on the determination of the 500-mbar temperature field which appears qualitatively different.

The Galileo Photopolarimeter-Radiometer (PPR) experiment was designed to cover a broad wavelength range (410 nm to more than 45 μm wavelength) in order to produce a synoptic set of measurements on properties of cloud particles, temperature variations, and local radiation budget in Jupiter, and to provide information on satellite surface characteristics (1). This first report on PPR observations of the Jovian system during the primary orbital mission will concentrate on measurements of thermal infrared radiometric properties of the satellites and Jupiter.

Ganymede

We mapped the 17-μm brightness temperatures over the morning and midday portions of Ganymede's southern hemisphere (Fig. 1) with 200-km (~4.5° latitude) spatial resolution, substantially better than the 500-km resolution Voyager IRIS thermal maps of Ganymede (2). A strong anticorrelation between albedo and temperature is evident, which was also seen at lower spatial resolution by Voyager. The magnitude of the temperature variations is roughly consistent with the variation in absorbed sunlight, assuming surface thermal inertia is constant with albedo. Initial inspection does not reveal any temperature variations uncorrelated with albedo. Maximum brightness temperature is 152 K, shortly after noon in the equatorial portions of Galileo Regio, compared to maximum Voyager IRIS 17-μm brightness temperatures on this hemisphere of Ganymede of 149 K (2). This small discrepancy can be accounted for by the lower albedo of the region at the subsolar point, and Ganymede's slightly smaller heliocentric distance, compared with the Voyager observations. Voyager observed the afternoon cooling curve only: the PPR map provides our first view of the morning heating curve. Morning temperatures are more than 10 K warmer than predicted by 1-layer, 2-layer, or 2-component models fitted to Voyager data and groundbased eclipse cooling data (2), so substantial revision of our understanding of Ganymede's thermal properties will probably be necessary. Extensive nighttime observations of Ganymede's thermal emission were also obtained, but these have not yet been fully r edu iced.

Europa

1'1 'R also provided the first measurements of the subsolar emperature on Europa. Observations at 37 μm along a 400-km (15°-wide) strip give a subsolar brightness temperature of 128 K, which, when combined with Voyager 2 observations of the equatorial evening terminator temperature, about 90 K, can be fit with a homogeneous thermophysical model with a bolometric albedo of ().(ii; and a thermal inertia of 2.6 × 10" erg 131 r2 s $^{1/2}$ 1(' ^{1} Although the homogeneous model ignores probable vertical and horizontal variations of thermal properties as well as subsurface sunlight penetration (4), it does allow comparison with the other icy Galilean satellites, which have significantly higher homogeneous-model thermal inertias: 7 × 101 for Ganymede and 5 × 10" for Callisto, derived from Voyager data (1). This unusually low thermal inertia may be related to the unusually high regolith porosity inferred from photometry of Europa (5).

Io

PPR observations of 10 included the first global observation of Io's nightside thermal emission. Equatorial trailing-side 37-μm brightness temperatures at a local time near 9 PM, averaged over the I 600-km (50°) field of view, are in the range S() -85 1<. This is consistent with Voyager observations of smaller regions on the nightside (6). However, volcanic heat flow estimates by Veeder *et al.* (7) assumed that 80% of Io's surface had a diurnally- constant temperature of about 109 K. Assuming an emissivity of 0.9, this would give much higher nighttime 37-μm brightness temperature of 101 K, plus an additional substantial contribution from the hot spots. The low nighttime thermal emission suggests that more of the absorbed sunlight is re-radiated from the day side. ?111(1 thus that less Of the dayside emission is due to volcanic heat than assumed by Veeder *et al.* Estimates of volcanic heat flow may thus require revision.

Jupiter

The relative length of the G1 encounter period enabled the large Great Red Spot (GRS) feature to be mapped, in a strategy which coordinated synoptic observations by all four remote sensing instruments. The PPR derived the tropospheric temperature field of the GRS and vicinity. The temperature sounding experiment uses four discrete filters whose effective wavelengths are at approximately 15. 22, 25 and 37 μm (660, 450, 405 and 270 cm^{-1}), respectively (1). At these wavelengths, the opacity of the atmosphere is dominated by the collision-induced absorption of H_2. Because H_2 is well mixed, the outgoing thermal radiance can be inverted to retrieve the kinetic temperature field. The filter selection provided as wide a vertical range of atmospheric sampling as possible, with the peak of the outgoing thermal radiation in each channel ranging from levels of 200 fill'oll~,ll 700 mbar total pressure (8). The 250-mbar temperature field was determined largely by the measured radiance fields at 1 5. 22 and 25 μm, and the 500-mbar temperature field was determined largely by the measured radiances at 22 and 37 μm. The P-J2N()()-kill (2.2° longitude) diameter fields of view resolve the GRS about two times better than the Voyager IRIS zonal and meridional scans (9,10), about the same as the Voyager IRIS map of its interior (9), and about two times better than diffraction-limited ground-based telescopes such as the 3-m NASA Infrared Telescope Facility near 20 μm (12).

The 250-mbar map (Fig. 2) clearly shows that the GRS is cold with respect to its surroundings. The coldest temperatures in the center are about 107±1 K, with variations that ()() not exceed the expected measurement uncertainties. This temperature minimum area is confined 1,() 314 - 328° W longitude, east and west of which the temperatures rise to values of ~111±1 1{ in a broad axisymmetric region between ~14° - 23° S known as the South Tropical Zone (STrZ). The location of the steepest zonal (east-west) thermal gradient corresponds 10 the location of the innermost dark area of the 11()-11111 image of the GRS. To the 1101'111 of this dark area, however, temperatures remain as cold as at the center, although over a narrower longitude range of 318 - 324° W. To the south, on the other hand, temperatures rise to values of 114±1 K, with the steepest gradient n() further south than 37°S and just 11[)1'11) of the visually dark ring surrounding the GRS. Relatively warm (116 - 119 1<) temperatures are apparent east of 308° W longitude and north of 14oS latitude, and the warmest temperatures (117-120 K) are evident west of 338° W and north of 12° S in the extended region map. These are both generally coincident with visually dark areas associated with the broad axisymmetric region (~8° - 14° S) known as the South Equatorial Belt (SEB). The region south of 14°S in the map of the extended area, is cooler, with temperatures of 114 - 116 K, and it is more coincident with the lighter area in the 410-nm map. The absolute temperatures derived are generally some 3 - 5 K colder than those reported by Voyager IRIS (Fig. 10 of ref. 9), possibly arising from a difference of absolute radiometric calibration. (h I the other hand, Fig. 1[) of ref. 9 also shows that the relative temperature variations are quite similar, although they are more symmetric in the meridional (1101 rth-south) direction.

The 500-mbar map (Fig. 2) is both similar to and different from the 250-mbar map. The coldest region in the center of the GRS is 21: K, but it is surrounded by a warmer ring of 24 28 K locate ust to he exterior of the boundary of the steepest 250-mbar temperature gradients (except in the nort). Exterior to this ring o the east, west and sout , temperatures are an intermediate 123 - 27 K. The region north of 12°S latitude and east of 308°W longitude, which is rela vely warm at 250 mbar, is also a warm 27 - 128 K. Unlike temperatures at 250 mbar, the entire extended region west of 335°W longitude appears o be the warmest at 128 - 131 K. The 500-mbar temperature differences between the interior and exterior of the GRS are generally consistent with those derived from Voyager IRIS (0). The bright ring around the GRS has the same morphology as the cloud-sensitive 5-μm emission observed by NIMS 12). This coincidence leads us to suspect the influence of spatially variable optical thickness of an NH_3 condensate cloud on the upwelling radiance measured at 22 and 37 μm, where brighter radiances indicate relatively clearer regions of the atmosphere. If the 500-mbar temperature field were uniform, then the optical thickness of a vertically thin NH_3 condensate cloud near 600 mbar pressure would need to increase by $\sim$10 o ma ch the mean observed 37-μm upwelling radiance. Accurate emperature sounding at this depth will require independent constraints on the cloud opacity, from NIMS data, from the PPR 45-μm cut-on filter measurements, or from ground-based NH_3 cloud-sensitive observations at 8.57 μm.

This observed emperature and cloud morphology are consistent with a model of the GRS as an anticyclonic vortex with high clouds and adiabatic cooling associated with upwelling motions (9,10), in which subsidence takes place at the immediate edge. Such a subsidence is consistent with the sudden rise in temperature and the appearance of an annulus of bright radiance at cloud-sensitive wavelengths which denotes a relative clearing in he cloud deck. Just as for the GRS itself, if one assumes that departures from constant emperatures along isobars are proportional to vertical winds, then the relatively cold 250-mbar temperatures north of the GRS that interrupt the normally warm SEB north of 12°N may indicate that the areas bright at 410 nm (Fig. 2) are regions of upwelling. By implica ion, these bright areas may be at least partly comprised of higher altitude particles than their darker surroundings. If his interpretation is valid, en the 500-mbar maps show little sensitivity to the presence of these clouds in the field to the west of the

GRS (longitudes to the west of 335° W), either because the upwelling is weak and the 500-mbar temperature difference too small to measure or that the particles in these clouds are so small as to be ineffective in scattering/absorbing the 22- and 37-μm radiation from which the 500-mbar temperatures are largely derived. However, exceptions to the correlation between visually bright and thermally cool areas abound, including the locally dark STrZ, which is relatively cool, or the visually bright region south of the GRS, a part of which is relatively warm. It is clear that substantial revision will be required of the simple paradigm that regions of upwelling, cold air are associated with saturated gas producing bright condensate particles.

The GRS temperature field will be further constrained by PPR G1 observations made at high emission angles which have been completely reduced. Further eludcidation of the relationships between the temperature field, circulation and cloud properties will also be made using G1 maps of nearly all longitudes over a narrow latitude strip just north of the equator (13).

References and Notes

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8. The recovery of temperatures uses the weighted-Chahine method, M. T. Chahine *J. Atmos. Sci.* **27**, 960 (1970), with additional weighting between the different filters according to their signal-to-noise ratios. The 1-σ equivalent $\delta T =$ 1.3 K for the 15-μ channel, 1.4 K for the 22μm channel, 0.8 K for the 25-μm channel, and 1.6 K for the 37-μm channel, assuming average atmospheric radiances and averages of 4 samples for the channels at 15, 22 and 25 μm and 16 samples for the 37-μm channel, corresponding to the observing sequence used for the data reported here. In the radiative transfer model, the He mixing ratio of 13.6% reported by Von Zahn *et al.* *Science* **272**, 849 (1996) was used, as was a value for the fraction of *para*-H_2 of 0.31 taken from Sada *et al.* (10).

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13. Not long after the start of these extensive observations, the PPR filter wheel was found to have remained at the position corresponding to the 37-μm discrete filter, despite commands to move to other filter positions. Therefore all subsequent measurements, including almost all the longitudes of this sequence, were made in the 37-μm discrete filter, and interpretation of these data without independent constraints on cloud properties. Our G1 calibration target observations were also made only with this filter, which will make difficult our re-examination of the radiometric calibration.

14. We express our gratitude for the support of the Galileo Mission Project for carrying this work through to its long-awaited final stage. We express particular thanks to A. Lacis and J. Hansen at NASA Goddard Institute for Space Studies for leadership during the early phases of the PPR instrument development, and for E. Russell for his ingenuity in designing an instrument of this spectral breadth. Thanks are due to J. Ferrier for his work in maintaining a radiometric calibration scheme for the instrument, and, most recently, to H. Peiris and C. Connor for their work in rapid processing of the data.

Figure Captions

Figure 1. False color representation of 17-μm daytime brightness temperatures on Ganymede (top) compared with albedo patterns derived from Voyager images (4) (bottom), smoothed to similar spatial resolution. Local time of day is given in the scale at the top: 12 "Ganymede hours" corresponds to local 110011." The anticorrelation of temperature and albedo is clearly seen. Streaky structure in the lower left of the temperature map is an artifact. Steps in the temperature scale are at 2- Kelvin intervals.

Figure 2. Maps of upper tropospheric temperatures at the Great Red Spot and vicinity at 250 and 500 mbar pressure. The region to the northwest was made in a separate observation sequence. Two separate shading schemes are used in order to enhance the observability of detail. The maps were made from a regular raster scanning pattern. The pattern for the 22-μm filter is illustrated in the top panel on a reference background provided by a 410-nm map of the same region created from a synoptic observation by the Hubble Space Telescope Wide Field camera kindly provided by Dr. Kathy Rages. The fields of view from the different filters were not coincident with one another. The value of a radiance measurement was assumed for the entire region covered by the instrument field of view. Unlike the satellite maps, the large Great Red Spot area with was not sampled with highly overlapping fields of view. Radiance in areas not covered by adjacent fields of view was interpolated. The area from which temperatures were derived is slightly smaller than the field of view map shown, as coverage by all filters was required.